Higgs in VV scattering

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1. Vector-boson scattering and EWSB

2. Higgs effective field theory

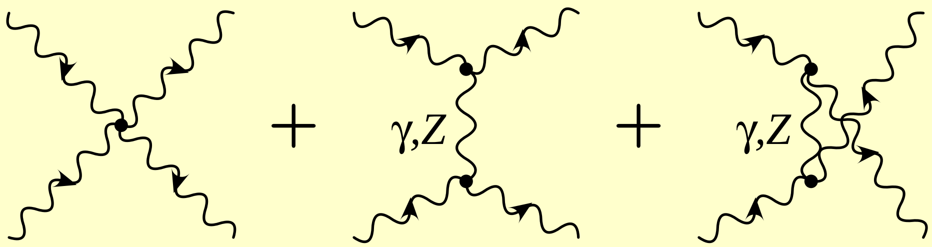
3. WW scattering at the LHC

Apologies: Not a comprehensive analysis/discussion of the topic!

Vector-boson scattering and EWSB

- Recent discovery of bosonic resonance with mass 125–126 GeV
  $\longrightarrow$ consistent with SM Higgs
- Still large uncertainty on its properties and details of EWSB
  - More information from improved rate/BR measurements
  - Direct test of role in EWSB through high-energy VV scattering

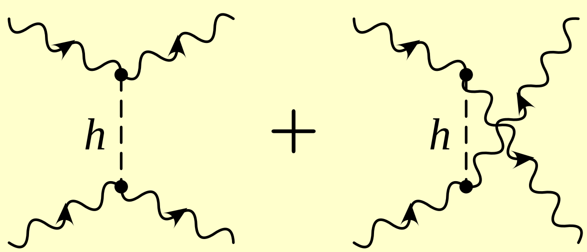
Example: $W_L^+ W_L^+ \to W_L^+ W_L^+$



$$\mathcal{M}_{\text{Gauge}} = \frac{t}{v^2} + \frac{u}{v^2}$$

$\longrightarrow$ Grows linearly for $s \to \infty$

SM Higgs contribution:



$$\mathcal{M}_{\text{Higgs}} = -\frac{1}{v^2}\left(\frac{t^2}{t-m_H^2} + \frac{u^2}{u-m_H^2}\right)$$

$$\mathcal{M}_{\text{Sum}} = -\frac{m_H^2}{v^2}\left(\frac{t}{t-m_H^2} + \frac{u}{u-m_H^2}\right)$$

Unitarity and EWSB

Possible new physics effects:

- Extended Higgs sectors (2 Higgs doublets, SUSY, etc.)
- Composite Higgs with energy-dependent form factors
- Higgs with non-perturbative self-coupling
- Additional (broad) resonances
- Higgsless models (125-GeV scalar is dilaton)
- ...

Some models disfavored by electroweak precision and LHC data

$\longrightarrow$ Independent check through VV scattering desirable
$VV = W^+W^+,\ W^+W^-,\ W^\pm Z,\ ZZ$

Strong dynamics

Rationale:

- Known mechanism in other cases (QCD, superconductivity, ...)
- Electroweak scale is natural (log. gauge coupling running)

$$\alpha_{\mathsf{TC}}^{-1}(\Lambda) - \alpha_{\mathsf{TC}}^{-1}(\Lambda_{\mathsf{GUT}}) = \frac{b_{\mathsf{TC}}}{8\pi} \ln(\Lambda/\Lambda_{\mathsf{GUT}})$$

$$\Rightarrow \quad \frac{\Lambda_{\mathsf{break}}}{\Lambda_{\mathsf{GUT}}} = \exp\left(-\frac{8\pi/b_{\mathsf{TC}}}{\alpha_{\mathsf{TC}}(\Lambda_{\mathsf{GUT}})}\right)$$

- Prediction: Higgs-like particle is composite scalar

Constraints:

- Model-building for quark/lepton masses
- EW precision data / FCNCs
- Direct searches for light pseudo-Goldstone bosons

Effective field theory

(slide stolen from B. Grinstein)

- H as PGB
  - Similar to dilaton, but not the same. Still predictive
  - Precision probes above still as relevant.

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SILH}} &= \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)+\frac{c_T}{2f^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(H^\dagger\overleftrightarrow{D}_\mu H\right)\\
&-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3+\left(\frac{c_y y_f}{f^2}H^\dagger H\bar{f}_L H f_R+\text{h.c.}\right)\\
&+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)(D^\nu W_{\mu\nu})^i+\frac{ic_B g'}{2m_\rho^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)(\partial^\nu B_{\mu\nu})\\
&+\frac{ic_{HW}g}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu}+\frac{ic_{HB}g'}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}\\
&+\frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu}+\frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}.
\end{aligned}
$$

"Strongly-Interacting Light Higgs" from hep-ph/0703164

Leading dim-6 Ops. The restricted form of this show the scheme has predictive power

Effective field theory

(slide stolen from B. Grinstein)

Assumptions and program:

- No non-SM fields needed below compositeness scale Λ
- Form factors admit Taylor expansion
- "Effective" lagrangian from SM fields only, with Poincare and gauge invariance
- Include non-renormalizable operators, suppressed by Λ
- Form factor Taylor expansion = operator derivatives expansion
- Study constraints from OTHER effects of same operators
- Graduate with PhD thesis

Example:

$$\mathcal{L} = \cdots + \lambda_b H \bar{q}_L b_R + \frac{c_b}{\Lambda^2} \partial_\mu H \bar{q}_L \partial_\mu b_R + \cdots$$

gives a form factor as above. Gauge invariance $\Rightarrow$

$$\mathcal{L} = \cdots + \lambda_b H \bar{q}_L b_R + \frac{c_b}{\Lambda^2} D_\mu H \bar{q}_L D_\mu b_R + \cdots$$

Effective field theory

- Modified (energy-dependent) couplings

$$e.g. \qquad g(HWW) = g\left(1 + \frac{a}{\Lambda^2} + b\frac{q^2}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})\right)$$

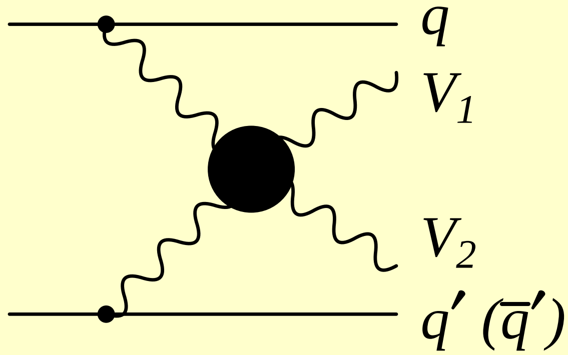
- (Composite) Higgs boson does not achieve full VV unitarization
  $\longrightarrow$ New resonances with $m \sim \Lambda \gtrsim 1$ TeV

Analysis of VV scattering:

- Measurement of role of Higgs boson in unitarization
- Test of modified couplings (in particular q^2 piece)
- Search for extra resonances
  ($e.g.$ additional Higgs bosons, techni-vector mesons, ...)

WW scattering at the LHC

Production at hadron colliders:



1. Apply smart cuts on vector-boson fusion (VBF) topology:
   $\longrightarrow$ two jets with large rapidity gap
2. Count events or analyze m_{VV}

Problem: typical event rate $\sim$ 0.1–0.5 fb at $\sqrt{s} = 14$ TeV

Duncan, Kane, Repko '86
Dicus, Vega '86
Kleiss, Stirling '88
Barger, Cheung, Han, Phillips '90
Baur, Glover '90
Dicus, Gunion, Vega '91
Dicus, Gunion, Orr, Vega '92
Bagger et al. '94,'95
Iordanidis, Zeppenfeld '98
Butterworth, Cox, Forshaw '02
Alboteanu, Kilian, Reuter '08
Englert, Jäger, Worek, Zeppenfeld '09
Ballestrero, Bevilacqua, Maina '09
ATLAS '09
Ballestrero, Franzosi, Maina '11
Doroba et al. '12

and others...

Matrix Element Method

Matrix Element Method (MEM):

Kondo '88,'91
Dalitz, Goldstein '92
DØ collaboration '99,'04

Likelihood that measured event, $\mathbf{p}_i^{\text{vis}}$, agrees with theoretical matrix element M_α:

$$\mathcal{P}(\mathbf{p}_i^{\text{vis}}|\alpha) = \frac{1}{\sigma_\alpha} \int dx_1 dx_2 \, \frac{f_1(x_1) f_2(x_2)}{2 s x_1 x_2} \times \left[\prod_{i \in \text{final}} \int \frac{d^3 p_i}{(2\pi)^3 2E_i} \right] |M_\alpha(p_i)|^2 \prod_{i \in \text{vis}} \delta(\mathbf{p}_i - \mathbf{p}_i^{\text{vis}})$$

For sample of N events:

$$\chi^2 = -2 \ln(\mathcal{L}) = -2 \sum_{n=1}^{N} \ln \mathcal{P}(\mathbf{p}_{n,i}^{\text{vis}}|\alpha)$$

(+) Uses complete event information
(+) Effective for small event samples
(+) Works well also with invisible final-state objects

Strongly Interaction Light Higgs (SILH)

Class of models with strong dynamics at $\Lambda \sim 4\pi f > 1$ TeV
and light composite Higgs boson
(here $m_H = 125$ GeV)

Guidice, Grojean, Pomarol, Ratazzi '07

- Higgs couplings to SM particles reduced by $1/\sqrt{1 - c\,v^2/f^2}$, $c \sim \mathcal{O}(1)$
- Full unitarization for $M_{WW} \to \infty$ by heavy resonances ($m \sim$ few $\times\, f$)
  $\longrightarrow$ May be beyond reach of LHC

Consider process: $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'} \quad (\ell^{(\prime)} = e, \mu)$

$(-)$ Relatively low event rate

$(-)$ Final state cannot be reconstructed kinematically

$(+)$ Clean final state (no jet ambiguity)

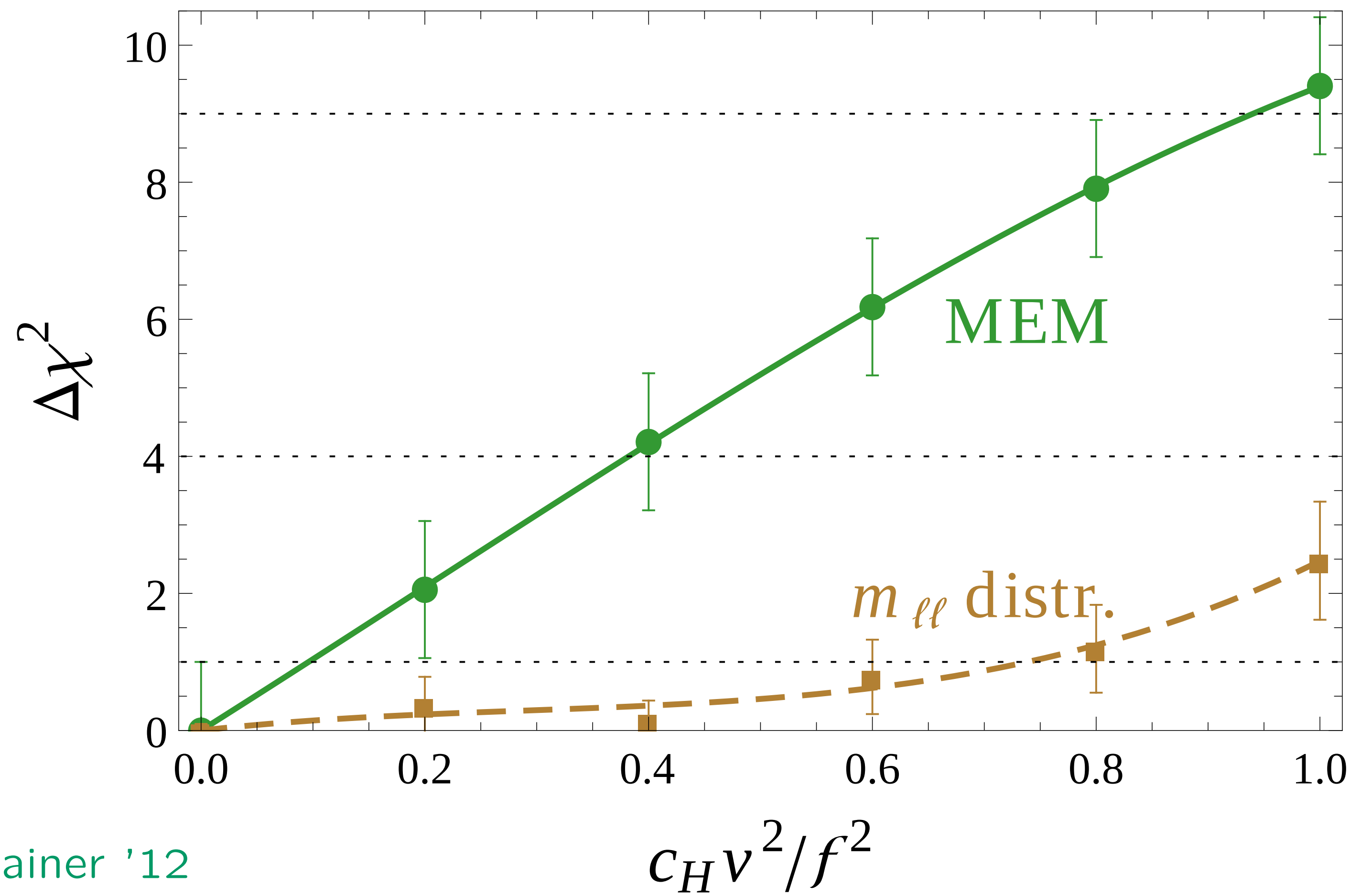
$(+)$ Low background

Results: SILH

MEM: 100 events at $\sqrt{s} = 14$ TeV for $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$

Traditional analysis: $m_{\ell\ell}$ distribution, 2 bins for $m_{\ell\ell} \in [0, 1000]$ GeV,

(results compatible with Ballestrero, Franzosi, Maina '11)



Freitas, Gainer '12

Two Higgs Doublet Model (THDM)

Higgs-like particle with $m = 125$ GeV has been observed

$\longrightarrow$ Could be one of two CP-even Higgs states h^0 and H^0 ($m_{h^0} = 125$ GeV)

$\longrightarrow$ Both needed for complete unitarization

Mixing angles:

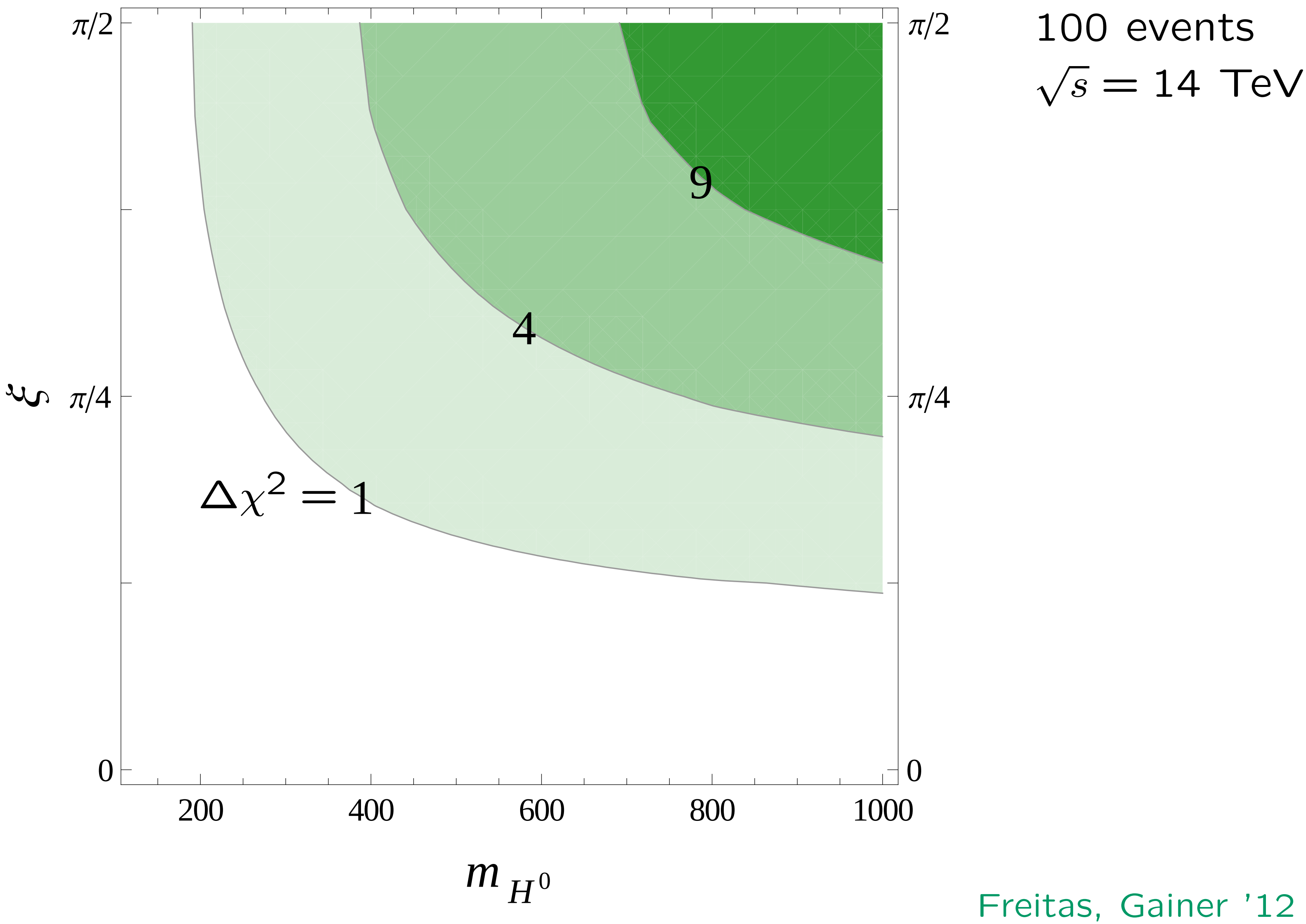
$$h^0 = \cos\alpha\ H_1^0 - \sin\alpha\ H_2^0$$
$$H^0 = \sin\alpha\ H_1^0 + \cos\alpha\ H_2^0$$

$$\frac{g(h^0WW)_{\mathrm{THDM}}}{g(HWW)_{\mathrm{SM}}} = \cos(\beta-\alpha) \equiv \cos\xi$$

$$\frac{g(H^0WW)_{\mathrm{THDM}}}{g(HWW)_{\mathrm{SM}}} = \sin(\beta-\alpha) \equiv \sin\xi$$

$$\tan\beta = \langle H_2^0\rangle / \langle H_1^0\rangle$$

Results: THDM



Thank you for your attention!

Backup slides

WW scattering and MEM

Consider process: $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'} \quad (\ell^{(\prime)} = e, \mu)$

$(-)$ Relatively low event rate

$(-)$ Final state cannot be reconstructed kinematically

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Main backgrounds:

- Intrinsic $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$
  (contributions without $W_L^+W_L^+$ scattering)
- $pp \to t\bar{t} \to jj\ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'}$ Doboda et al. '12
  (due to wrong charge identification for $\mathcal{O}(1\%)$ of hard lepton tracks)

Implementation of MEM for WW scattering

Partonic process: $q\bar{q} \to q'\bar{q}'W^+W^+ \to q'\bar{q}'\ell^+\ell'^+\nu_\ell\nu_{\ell'}$ $(q, q' = u, d, s, c)$

- Analysis at parton-level (jet smearing functions are straightforward but computing intensive) DØ '04, Fiedler et al. '10
- Private code for likelihood weights and cross-section normalization
- MADGRAPH/MADEVENT/MADWEIGHT for cross-checks
- Simulation of "experimental" events with MADEVENT ($m_h = 125$ GeV)

Preselection cuts:

$p_{\mathrm{T},\ell} > 20$ GeV	$p_{\mathrm{T,j}} > 30$ GeV	$\lvert\eta_\ell\rvert < 2.5$	$\lvert\eta_j\rvert < 5$	(acceptance)
$\Delta R_{jj,\ell j,\ell\ell} > 0.4$				(isolation)
$\lvert\eta_{j_1} - \eta_{j_2}\rvert > 4$	$\lvert\eta_j\rvert > 1$	$m_{j_1 j_2} > 100$ GeV		(VBF cuts)
$m_{\ell j} > 190$ GeV				($t\bar{t}$ bkgd.)

SM cross-section ($\sqrt{s} = 14$ TeV): $\sigma = 0.59$ fb
$\longrightarrow$ 100 events with $\mathcal{L} \sim 170$ fb^{-1}